Introduction to fronts, Part I
Onset of Indian monsoon
The first 'obs' book
Summer School on The Storm

THE METEOROLOGICAL MAGAZINE

December 1988

Met.O.982 No. 1397 Vol. 117

METEOROLOGICAL OFFICE Met.O.982

THE METEOROLOGICAL MAGAZINE

No. 1397, December 1988

551.515.8

An introductory review of fronts. Part I: Theory and observations

D.A. Bennetts, J.R. Grant and E. McCallum

Meteorological Office, Bracknell

Summary

This paper, on frontal meteorology, is one of a series of teaching papers on mesoscale meteorology developed at the Meteorological Office College. Part I describes important dynamical aspects of both the formation and structure of frontal zones, and Part II illustrates the main features through a case-study of a cold front which crossed the United Kingdom on 13 January 1983.

Here, in Part I, simple conceptual models are described which should help forecasters to understand frontal zones and thereby lead to a better appreciation of the data available from the increasing number of mesoscale observing systems that are coming into operational use. The paper is not intended to be a comprehensive review.

1. Introduction

Over the past decade there has been a considerable number of theoretical and observational studies into the formation and structure of frontal zones. Much of this work has followed directly from the new mesoscale observational techniques that were developed in the late 1960s and 1970s, and from modern computers that permit numerical modelling to take place at a similar spatial resolution to that of the observational data.

These mesoscale observational systems are now becoming available at forecasting offices. It is therefore appropriate to try and pull together the results from the many research papers, and give an overview of the meteorological processes that give rise to the mesoscale features that are now observed routinely within frontal systems.

The paper is divided into two parts. Part I discusses how frontal zones form, what determines their overall structure and the nature of sub-frontal-scale perturbations. Part II (Bennetts *et al.* 1989) is a case-study of an active cold front that crossed the United Kingdom on 13 January 1983 and is used to illustrate many of the conceptual models developed in Part I.

In Part I, every effort has been made to bring out the meteorology of the various features and to produce simple conceptual models. The paper is written with the practising forecaster in mind, and is intended to provide an understanding of the mesoscale features that are readily observed, both on satellite pictures and through the UK weather radar network data. To this end, many of the mathematical details are omitted.

2. Frontal theory

A great deal can be learnt about fronts by considering adiabatic, frictionless flow in a dry atmosphere. Water vapour will be important in describing some of the sub-frontal-scale features discussed later but, at this early stage in the paper, it is an unnecessary complication.

Consider a simple case in which a straight front is moving with the geostrophic wind speed, u_g (suffix 'g' denotes geostrophic) — the coordinate system and orientation of the front are given in Fig. 1(a). To understand the behaviour of the front it is helpful to consider motion relative to the front. In this case the situation is that given in Fig. 1(b). Note that now the x component of the wind relative to the front, u, is simply the ageostrophic wind.

Observations of fronts have shown that typical length scales along the front, L, and across the front, l, are $L \approx 1000$ km and $l \approx 100$ km, and that typical velocity scales of the relative flow along the front, v, and across the front, u, are $v \approx 10$ m s^{-1} and $u \ll v$. Consequently, to a good approximation, a front can be viewed as being two dimensional, with no change in structure along its length. Also, following Hoskins and Bretherton (1972), it can be shown that a consistent set of equations describing the flow relative to a front are as follows

$$v = v_g \text{ where } v_g = f^{-1}\, \delta\phi/\delta x \qquad \ldots \qquad (1)$$

$$dv/dt + fu = 0 \qquad \ldots \qquad (2)$$

$$\delta\phi/\delta z = g\,\theta/\theta_0 \qquad \ldots \qquad (3)$$

$$d\theta/dt = 0 \qquad \ldots \qquad (4)$$

$$\delta u/\delta x + \delta w/\delta z = 0 \qquad \ldots \qquad (5)$$

where θ_0 is a reference temperature, f is the Coriolis parameter, g is the gravitational acceleration, t is the time and ϕ is the geopotential height. In the context of this paper the vertical coordinate, z, can be thought of as the geometric height, although in reality it is only equal to the geometric height in an isentropic atmosphere. Similarly w can be taken to be the vertical velocity. A detailed discussion of this coordinate system is given in Hoskins and Bretherton.

The most important point to note is that equation (1) states that the wind component parallel to the front is always in geostrophic balance. A consequence of that statement is that the ageostrophic component of motion (u,w) is confined to the cross-frontal plane.

Furthermore, geostrophic balance implies thermal wind balance; elimination of ϕ from equations (1) and (3) leads to the thermal wind equation

$$f\,\delta v/\delta z = (g/\theta_0)\,(\delta\theta/\delta x). \qquad \ldots \qquad (6)$$

The form may be unfamiliar, but the link between the vertical gradient of velocity and the horizontal gradient of temperature can be recognized.

From equations (2) and (5) it will be seen that the ageostrophic motion is driven through changes in the air motion parallel to the front, i.e. through changes in dv/dt. The form of this ageostrophic motion has been described by Hoskins (1978), but the mathematics are complex and a detailed exposition is not appropriate here. The importance lies in the results of the work which show that in a typical frontal zone the streamlines of the cross-frontal (ageostrophic) flow form closed loops, as shown in Fig. 2. The direction of the circulation depends on the nature of the baroclinic zone and, in the configuration of

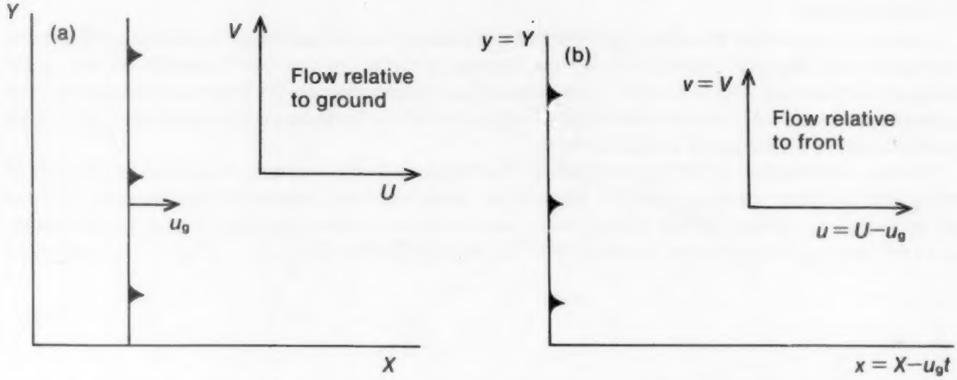


Figure 1. The coordinate systems and orientation of the front, (a) relative to the ground and (b) relative to the front. See text for explanation of symbols.

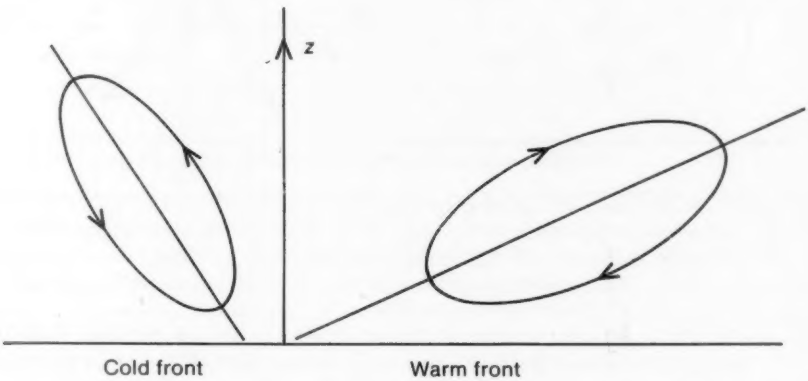


Figure 2. Schematic diagram of the cross-frontal ageostrophic motion. The direction of circulation depends on the nature of the baroclinic zone.

Fig. 2 (which is drawn with the observer looking towards the low pressure), it is found that on the warm front the circulation is generally clockwise while on the cold front it is generally anticlockwise.

Not surprisingly, there are similarities between the model in Fig. 2 and the familiar concept of air ascending and descending along the frontal surfaces. It may seem odd that all the streamlines in Fig. 2 cross the frontal zones, but that is due to the simplifications that have been made in developing the theory, in particular the omission of boundary-layer friction and ageostrophic effects near the jet stream. Both omissions will be discussed in more detail later in the paper.

In summary, the purpose of this section was to introduce the equations of frontal theory in their simplest form, and to show that the results of the theory are in agreement with the well established, observationally based concepts.

3. Frontogenesis

A front delineates the boundary between two different air masses and hence its position depends on the large-scale synoptic flow. However, the internal structure of the front depends on very local (mesoscale) processes. Unfortunately, such a separation of roles obscures the important linkage between synoptic and mesoscale motion — a linkage which is vital for the formation and maintenance of a frontal discontinuity. This linkage is discussed below.

Hoskins and Bretherton (1972) identify several synoptic-scale flow patterns that have the property of being able to tighten thermal gradients. Three of the most important in terms of the formation of fronts are shown in Fig. 3; Figs 3(a) and 3(b) represent motion in a horizontal plane, and 3(c) represents motion in a vertical plane. Regions such as depicted in Figs 3(a) and 3(b) are illustrated in Fig. 4. The label 'A' in

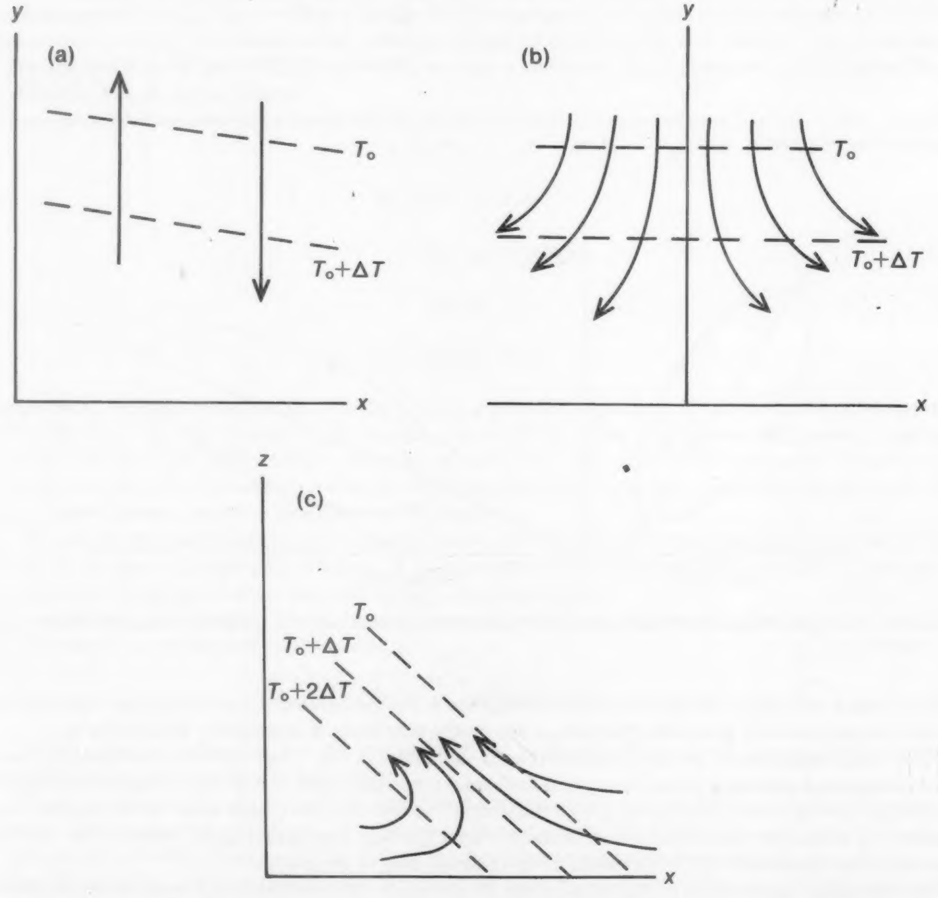


Figure 3. Three flow configurations which can intensify horizontal temperature gradients, (a) horizontal shear, (b) horizontal deformation, and (c) vertical deformation.

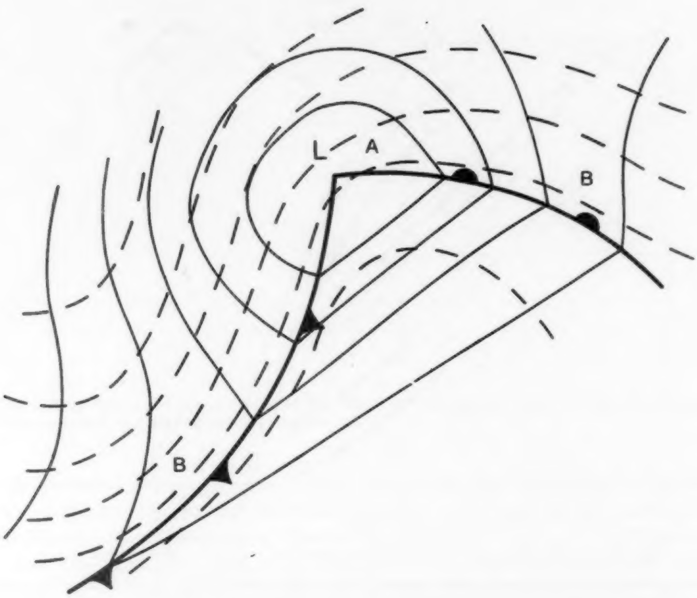


Figure 4. Depicted is a simplified schematic baroclinic wave. Dashed lines represent thermal thickness lines and solid lines the 1000 mb contours. A and B mark areas of horizontal shear and deformation, respectively.

Fig. 4 indicates a region in which the thermal gradient is being tightened due to a change in wind direction (as in horizontal shear, Fig. 3(a)) and 'B' regions of horizontal deformation (as in Fig. 3(b)). In both regions there is a tightening of the thermal gradient ($\delta\theta/\delta x$) and hence, because there is always thermal wind balance parallel to the front, a corresponding increase in $\delta v/\delta z$, i.e. the along-front wind component, v, increases with time, $dv/dt \neq 0$. Reference to the horizontal momentum equation (2) shows that if $dv/dt \neq 0$ then $u \neq 0$ and hence, from the continuity equation, $w \neq 0$. In consequence a tightening of the horizontal thermal gradient induces cross-frontal ageostrophic motion.

Consider now the frontal zone. The nature of the cross-frontal ageostrophic circulation has already been shown in Fig. 2. In Fig. 5, this circulation is superimposed on the potential temperature field (NB there is a simplification in this diagram that will be readily apparent when frictional effects are discussed in section 4); note particularly the region at the bottom of Fig. 5 at 'C', between the ascending and descending branches of the circulation, in which the temperature gradient is being compressed and hence strengthened (on the warm side of the baroclinic zone); compare this with Fig. 3(c). Therefore the cross-frontal ageostrophic motion tightens the thermal gradient.

Thus frontogenesis is a positive feedback mechanism between synoptic and mesoscale motion that works as follows:

(a) synoptic-scale horizontal deformation fields locally tighten the thermal gradient,

(b) since there must always be thermal wind balance along the front this implies an acceleration of v which induces an ageostrophic cross-frontal circulation, and

(c) the induced cross-frontal circulation further tightens the horizontal temperature gradient, which increases v ... *ad infinitum*.

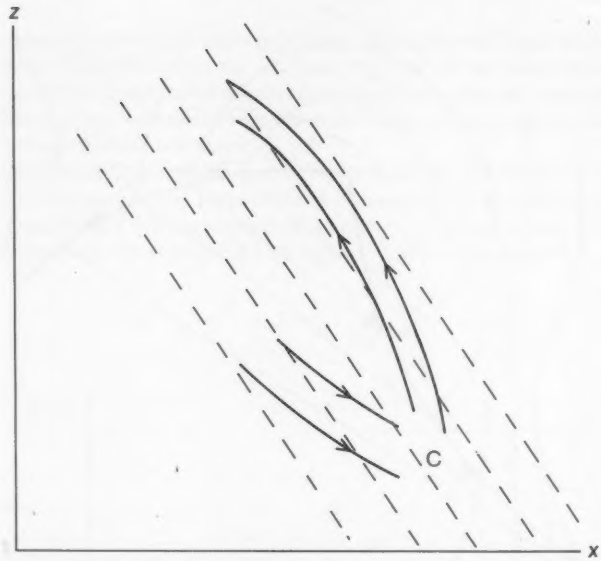


Figure 5. Cross-frontal ageostrophic circulation superimposed on the potential temperature field. Dashed lines represent lines of potential temperature and solid lines the streamlines of the cross-frontal circulation (from Fig. 2). The region, C, between the ascending and descending air is a region in which potential temperature lines are being compressed and hence $\delta\theta/\delta x$ is increasing.

The process is finally brought to a steady state by the effects of turbulent diffusion, when the frontal zone is typically about 1 km deep. This is, not surprisingly, a similar depth to the boundary layer, the physical processes which lead to the generation of turbulent diffusion being the same in both cases.

In summary, the theory provides a satisfactory explanation for the observation that fronts form on time-scales shorter than might be expected from consideration of the strength of the synoptic-scale deformation alone. It also accounts for the fact that fronts often maintain their identity for some time after synoptic deformation fields have weakened.

4. The conveyor belt

In section 2, fronts were discussed in the context of a frictionless environment. However, the effects of surface friction are important. Indeed, they are part of the reason why cold fronts have, in general, a steeper slope ($\approx$ 1:70) than warm fronts ($\approx$ 1:150).

Browning and Pardoe (1973) discussed a conceptual model that described the flow in the boundary layer associated with a surface cold front. They found a warm, low-level conveyor belt, typically 1 km deep and 100 km across, situated just ahead of the surface cold front. The warm moist air contained within the conveyor belt was subject either to 'rearward sloping ascent' whereby some of the warm air leaked up over the cold front or 'forward sloping ascent' where all the air remained within the conveyor belt, eventually ascending the warm frontal surface. These two models are depicted in Figs 6(a) and 6(b) (after Browning and Pardoe 1973). The model in Fig. 6(a) implies an active cold front while the model in Fig. 6(b) results in an active warm front. Observations confirm that depressions do not normally have both frontal zones active simultaneously.

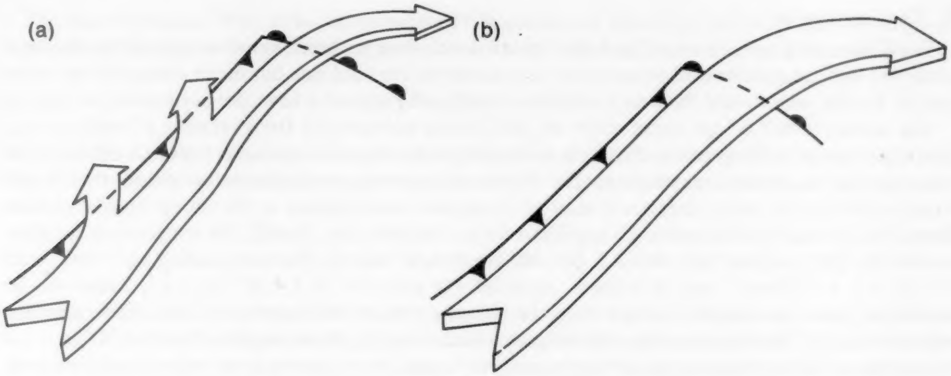


Figure 6. The motion within the warm conveyor belt relative to the surface fronts. Depicted are two models showing (a) rearward sloping ascent, and (b) forward sloping ascent.

Because the conveyor belt is a low-level feature, surface friction effects play a major role in its detailed structure. Consequently the air motion within it has a significant ageostrophic component and this modifies the cross-frontal (ageostrophic) circulation depicted in Fig. 2, the modification being strongest at the bottom of the circulation, where the simplified model depicted streamlines actually crossing the frontal surface. A full description of the interaction of the conveyor belt with the cross-frontal circulation has not been developed to date, but a conceptual model is shown in Fig. 7. In this model, air does not cross the frontal zone near the ground. Instead, the ascending branch of the cross-frontal circulation is fed by warm-sector air, as shown in the 'rearward sloping ascent' model illustrated in Fig. 6(a). In reality, most fronts will exhibit aspects of both models, some air leaking up the frontal surface from the low-level conveyor belt, and some crossing the frontal surface near the ground.

Turning now to the upper part of the front, the model shown in Fig. 2 also depicts the streamlines crossing the frontal surface. This is again a region in which there is significant ageostrophic motion, in this case associated with the jet stream. Because air can now enter and leave the cross-frontal circulation via the jet there is no longer a need for the circulation, as shown in Fig. 2, to cross the frontal surface. Fig. 7 illustrates this by leaving the streamlines open within the upper-level jet. There is thus the opportunity both for dry, stratospheric air to be drawn down the frontal surface, and for moist, tropospheric air to be injected into the stratosphere, as has occasionally been observed.

The above concepts are brought together in a model developed by Browning and Pardoe (1973) from observational evidence. This model is shown in Fig. 8 and the similarities with Fig. 7 are self evident. One point does, however, require clarification and that is the behaviour at the nose of the front where the streamlines are almost vertical. Observations show that there is often a narrow region (5–10 km wide) of heavy convective rain (a squall line) coincident with the surface cold front. Such a region cannot be predicted by the models discussed so far in this paper, because the simplifications have effectively removed from the equations the ability to simulate convection, the moist processes having been omitted. Consequently the effects of this near-vertical motion at the surface cold front need to be taken into account when comparing the theoretical model, Fig. 7, with the observational model in Fig. 8.

In summary, this section has shown how the basic model of the cross-frontal circulation may be modified through the inclusion of turbulent diffusion and convective processes to produce a model that simulates many of the features found in case-studies.

5. The low-level jet

It will have been noticed from Fig. 8 that the low-level conveyor belt is shown as a jet. It has also been observed that the gradients of velocity are very strong on the cold side but much weaker in the warm sector. Firstly, why should there be a jet and secondly, why should it have this asymmetric structure?

The conveyor belt brings warm moist air close to the surface cold front creating a locally strong, horizontal temperature gradient. From the scale analysis developed in section 1, features such as the jet, which have a two-dimensional structure (i.e. they vary in character much more slowly along their length than in either of the other directions) must be in thermal wind balance in the 'along-front' direction. Hence the thermal wind equation (6) applies to the jet. Suppose that, locally, the temperature gradient created by the conveyor belt was 1 K per 100 km greater than in the surrounding air. Then, with $f = 10^{-4}\,s^{-1}$, $g = 10\,m\,s^{-2}$ and $\theta_0 = 280$ K equation (6) gives $\delta v \approx 3 \times 10^{-3}\ \delta z\,m\,s^{-1}$. Since the jet maximum occurs at a height of about 1 km then typically the jet core is some 2–5 m s^{-1} faster than the surrounding air. This figure agrees well with the values found by Browning and Pardoe (1973).

An interesting consequence of the above analysis is that, above the jet core, where $\delta v/\delta z$ becomes negative, there should be a region in which $\delta\theta/\delta x$ becomes negative. This point will be pursued in the case-study in Part II of this paper.

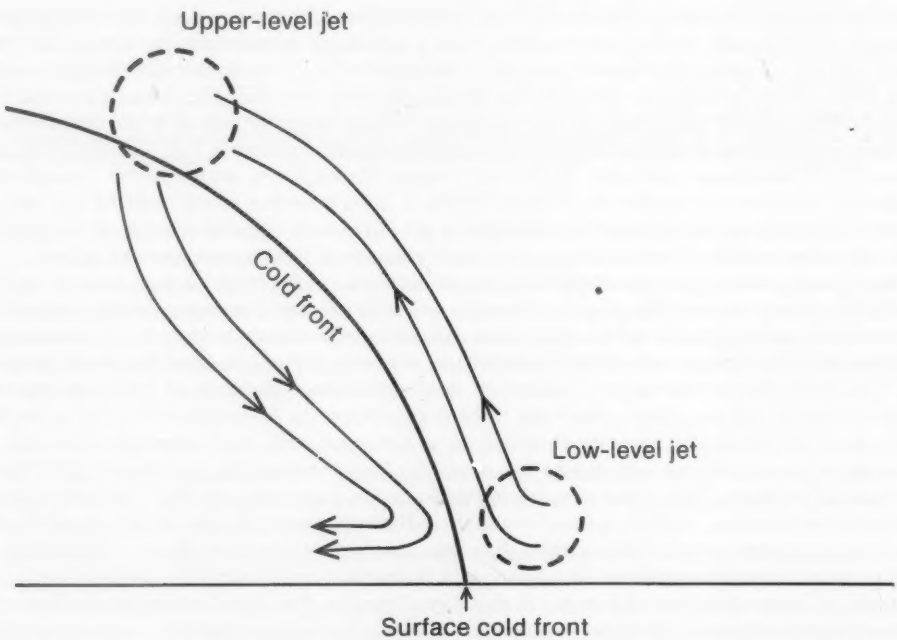


Figure 7. Cross-frontal ageostrophic motion when the effects of turbulent diffusion are included. Notice how the low-level jet acts as a source of air for the ascending branch and how the upper-level jet eliminates the need for the air to cross the frontal surface. Instead, air can enter and leave the jet stream, allowing dry stratospheric air to be brought down into the troposphere behind the cold front.

The second point is 'Why is the jet asymmetric?' Bennetts and Hocking (1973) showed that this was due to the difference in the vorticity on each side of the jet. The absolute vorticity, ζ, is defined as

$$\zeta = f + \delta V/\delta x + \delta U/\delta y$$

where U and V are the full components of velocity (not just those relative to the front — see Fig. 1(a)). However, because the variations along the jet are small compared with those across it, this equation reduces to

$$\zeta = f + \delta v/\delta x.$$

On the cold side of the jet nearest the front (see Fig. 8) $\delta v/\delta x$ is positive while on the warm side it is negative. Therefore on the warm side there is a limit imposed by the requirement that the absolute vorticity must not become negative, i.e. $\delta v/\delta x > -f$. Taking the jet maximum as 2–5 m s^{-1} faster than the surrounding air, this implies that $\delta x > 20$–50 km, i.e. on the warm side of the jet the horizontal gradient of velocity is weak and that the scale over which the jet decays is dictated by the difference between the maximum core speed and the ambient warm-sector air. If the difference is j m s^{-1} then the minimum distance is about $10\,j$ km. This is well illustrated in Fig. 8, the jet decaying on a scale of tens of kilometres.

On the cold side there is no such restriction and therefore the gradient can become very sharp.

6. Instabilities on a front

The concept of a warm conveyor belt ascending above the warm frontal zone gives the impression of uniform ascent. In consequence, it may be supposed that the precipitation falling from frontal regions would also be uniform. However, this supposition is false and in fact the precipitation patterns exhibit

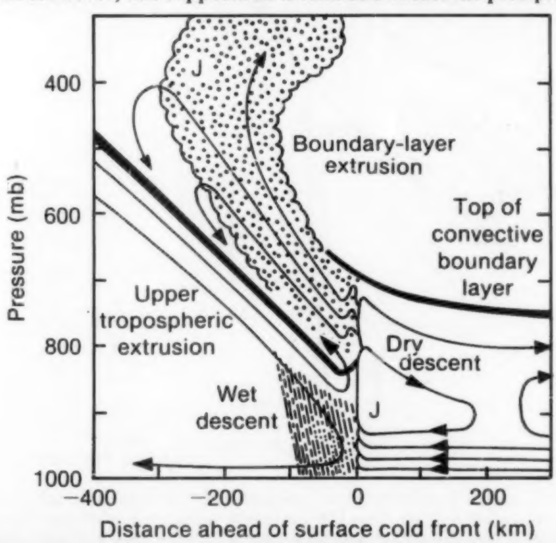


Figure 8. Schematic model of the airflow associated with a cold anafront. Thin lines are streamlines relative to the moving system. Thick lines represent the cold frontal zone and the top of the convective boundary layer. Regions of saturated ascent are stippled and jet cores, J, are marked (from Browning and Pardoe 1973).

features that are generally much smaller in scale than the frontal zone. Fig. 9 is a schematic diagram of various types of mesoscale rainbands that have been observed. Not all occur in every frontal system, indeed some systems exhibit none and have relatively uniform precipitation everywhere. However, each type of rainband has been seen, and can be expected to occur fairly frequently.

In this section the discussion will be confined to the wide rainbands, warm and cold frontal types 1a, 1b, 2 and 3b (see caption to Fig. 9). Type 3a is the cold frontal squall line that has already been discussed.

By way of an introduction to the subject, consider the absolute vorticity of a parcel of air in a frontal zone (this was introduced in section 5). Integrating the vorticity with respect to x, the cross-frontal coordinate, gives

$$\int \zeta \, dx = \int (f + \delta v/\delta x) \, dx = v + fx.$$

Now the momentum of a parcel of air is defined as mass × velocity and therefore the momentum of a unit mass of air is 'v'. Recalling the relationship between vorticity and absolute vorticity (dv/dx to $dv/dx+f$) it is fairly natural to define the quantity

$$M = v + fx$$

as the absolute momentum.

In the horizontal momentum equation (2), u may be written as dx/dt giving

$$d/dt\,(v+fx) = dM/dt = 0.$$

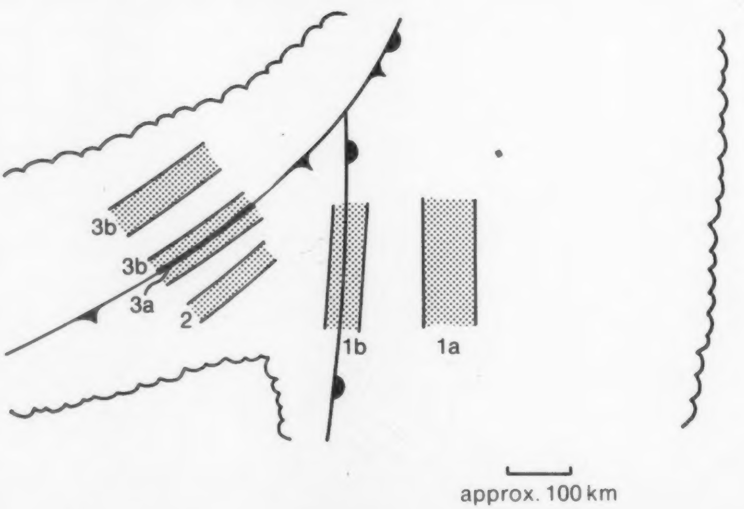


Figure 9. Schematic depiction of some types of mesoscale rainbands (stippled areas) observed in extratropical cyclones. The upper-level cloud shield of the cyclone is shown. Type 1: Warm frontal rainbands, of which type 1a occurs ahead of and parallel to the surface warm front, while type 1b coincides with the surface warm front. Type 2: Warm sector rainbands, which occur parallel to and ahead of the surface cold front. Type 3: Cold frontal rainbands, of which type 3a is very narrow and coincides with the surface cold frontal passage, while type 3b is wider and may straddle the narrow cold frontal rainband or lag behind it (after Matejka *et al.* 1980).

Therefore, within a frontal zone the absolute momentum of a parcel of air is conserved. Away from the frontal zone there is, of course, no such restriction on the air motion, and M need not be conserved. In the absence of diabatic effects, another conserved quantity is the wet-bulb potential temperature, θ_w.

Consequently, within a frontal zone, and only within a frontal zone, a parcel of air conserves both M and θ_w. If these two surfaces are parallel then conservation of both can be achieved (provided of course that the surfaces lie along streamlines). The case when they are not parallel is investigated below.

Consider Fig. 10 which shows two cases

(a) M surfaces steeper than θ_w surfaces, and
(b) θ_w surfaces steeper than M surfaces.

In both cases, if a parcel of air is displaced it will try to return to its original M and θ_w value, i.e. it will attempt to conserve both parameters. However, the restoring mechanisms are different. Restoration with respect to θ_w is achieved through buoyancy forces (as with convection) which act vertically, whereas restoration with respect to M is achieved through motion along geopotential surfaces, ϕ, which are nearly horizontal.

In Fig. 10(a) consider a parcel of air displaced along a line at an angle between the angles of the θ_w and M surfaces. Because both M and θ_w (generally) increase with height, the parcel enters a region of higher θ_w, it is colder than surrounding air, and therefore it sinks. Similarly it enters a region of lower M, the restoring force is to the right, in the direction of increasing M, and the resultant force opposes the motion (stability).

In Fig. 10(b) a similar displacement has a different effect. The parcel now enters a region of lower θ_w, is hotter than its surroundings and therefore rises; it also enters a region of higher M hence the restoring force is to the left, i.e. in the direction of decreasing M. Note now that the restoring force is in the same direction as the motion (instability). Given the slightest disturbances, the forces act to accelerate the parcel in the same direction as the initial motion.

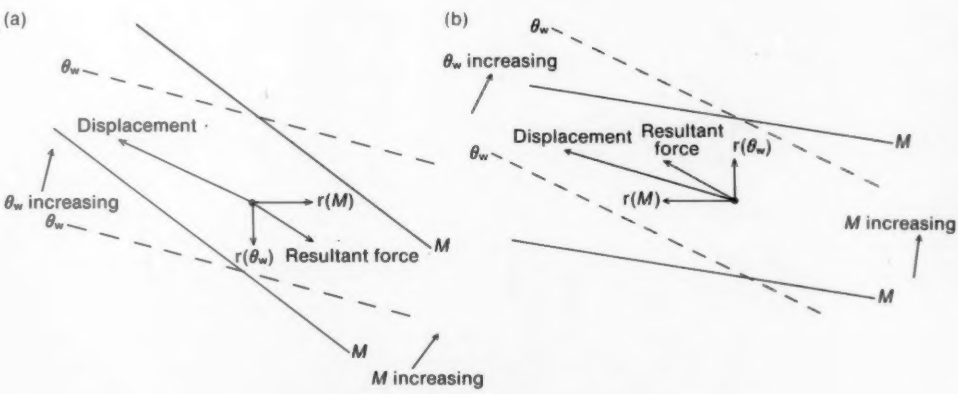


Figure 10. Restoring forces, r(M) and r(θ_w), generated when a parcel of air is displaced from M and θ_w surfaces. In case (a) the M surfaces are steeper than θ_w surfaces and the resultant restoring force opposes the displacement (stability), and in case (b) θ_w surfaces are steeper than M surfaces and the resultant restoring force is in the same direction as the displacement (instability).

This may be summarized as follows. If M and θ_w surfaces are parallel, then the atmosphere is 'neutral' and parcels of air may move easily along M and θ_w surfaces. If M surfaces are steeper (Fig. 10(a)) than θ_w surfaces, the atmosphere is 'stable' and external energy is required to generate movement. If θ_w surfaces are steeper (Fig. 10(b)) than M surfaces then the atmosphere is 'unstable' and energy is spontaneously released, allowing instabilities to grow until such time as all the (available) energy has been released, and the M and θ_w surfaces are again parallel.

The above analysis follows that given by Emanuel (1982). The instability is sometimes referred to as 'slantwise convection', slantwise because the motion takes place along θ_w and M surfaces, which are generally at a shallow angle to the horizontal, and convection because of the similarity with the way in which the convective process take place. An alternative name is 'Conditional Symmetric Instability' (CSI) (Bennetts and Hoskins 1979), because instability is conditional on the θ_w surfaces being steeper than the M surfaces, and because of the symmetrical shape of the resultant streamlines.

The instability forms as rolls within the frontal surface, similar to the closed circulation shown in Fig. 2, although on a smaller scale — typically there are two or three rolls within the frontal zone. In addition, because it can only develop in regions where the θ_w surfaces are fairly steep, a favoured region for this type of instability is within the ascending branch of the cross-frontal circulation.

Because the rolls develop within the frontal region they form as 'two-dimensional' features, i.e. variations along their length are small compared with those in the other two directions. In consequence, the rolls may be visualized as cylinders embedded within the frontal surface, with the major axis approximately parallel to the front — strictly they are parallel to the thermal field. There are obvious similarities between these rolls and the wide, warm and cold frontal rainbands which are typically some 50 km across, 100–200 km long, and form parallel to the frontal surfaces.

The streamlines of a single CSI roll produced from a numerical integration are shown in Fig. 11(a); depicted are the streamlines across the roll, i.e. in a plane perpendicular to the front. The size is larger than would be expected to develop in the atmosphere as the whole model domain (300 km in the horizontal by 10 km in the vertical) was pre-set to conditions suitable for the instability to grow. In the atmosphere, such regions are much smaller and therefore the rolls will be correspondingly reduced in size. It is envisaged that within a frontal zone there are likely to be two or three rolls as illustrated in Fig. 11(b).

An interesting property of any closed circulation is that, given sufficient time, it will 'overturn' any conserved quantity. In particular, a roll, embedded within a frontal zone, will overturn the θ_w surfaces, as illustrated in Fig. 12. Such a process leads to convective instability and therefore if CSI developed, for example, within a warm frontal zone, mid-level convective instability could result. Reports of convective development within warm fronts are fairly common and have hitherto been difficult to explain.

7. Frontal rainfall

It is now possible to visualize how non-uniformities develop within frontal precipitation. In Fig. 13(a) the air is shown ascending over a uniform frontal surface. The vertical velocity is (approximately) constant within the ascending air, and in consequence the rainfall will be (approximately) uniform as shown in Fig. 13(b).

If CSI develops within the ascending air then the motion due to the developing rolls (Fig. 13(c)) will be superimposed on the motion shown in Fig. 13(a) and the resultant vertical velocity profile will be as in Fig. 13(d). The consequent rainfall pattern is also shown in Fig. 13(d). In addition, as will be recalled from section 6, the rolls are capable of overturning θ_w surfaces and hence releasing convection. Lines of showers will therefore develop, embedded within the frontal surface. As the vertical velocity in the

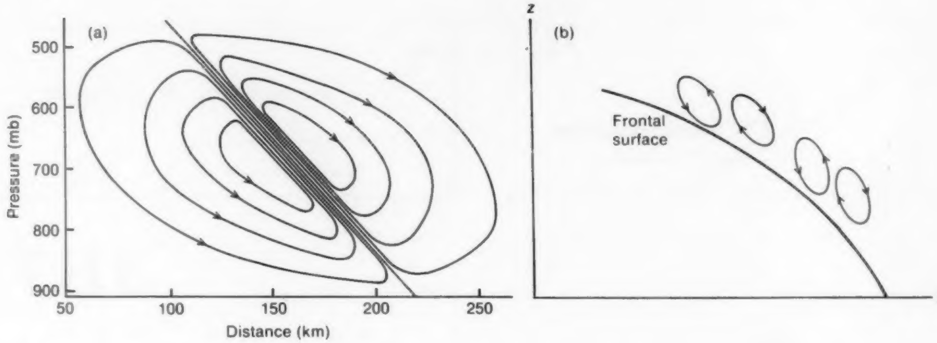


Figure 11. (a) A single Conditional Symmetric Instability (CSI) roll growing in a large, uniform domain which is everywhere unstable to CSI. The streamline intervals are in arbitrary units, but note the strong, narrow updraught in the centre of the disturbance compared with the weaker, descent regions, and (b) schematic diagram of CSI rolls growing in a more confined frontal region. Two rolls are depicted developing in the warm, moist ascending air.

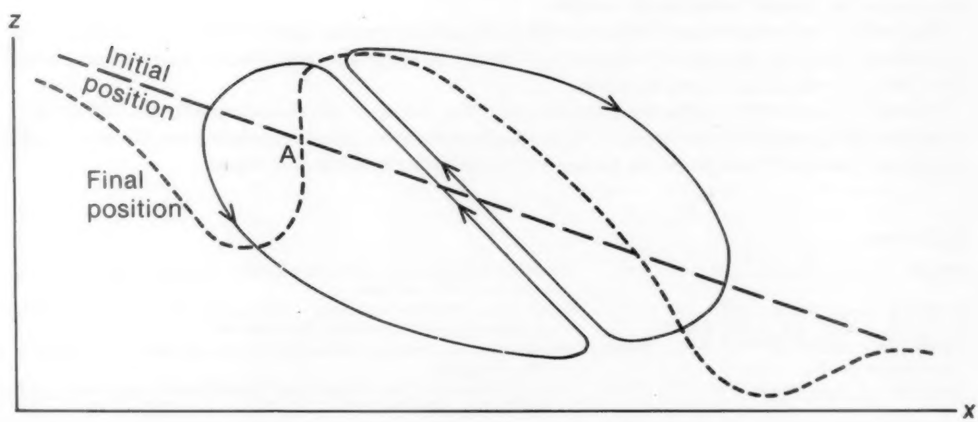


Figure 12. Schematic diagram showing how any closed circulation can 'overturn' a conserved quantity. Solid lines are streamlines and the heavily dashed line the initial position of the conserved quantity. The lightly dashed line shows the position after a period of time. Note how the line 'overturns' at the point marked A. If the conserved quantity were θ_w, convection would be likely to develop.

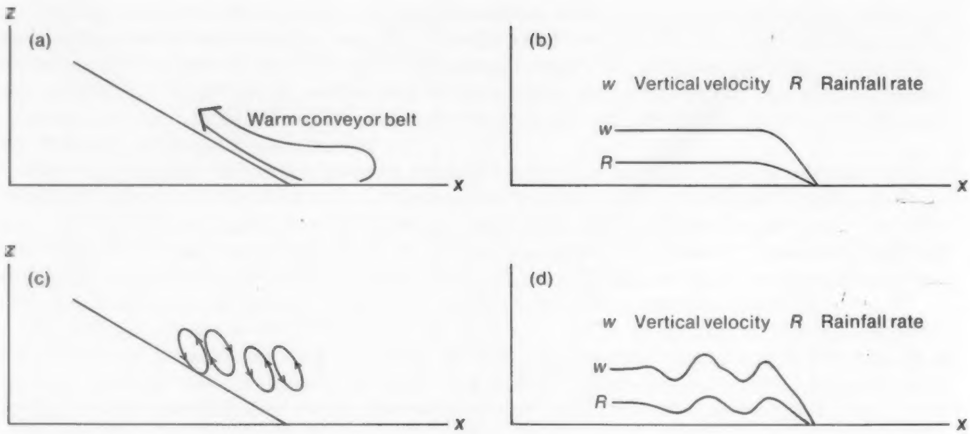


Figure 13. (a) Schematic diagram of air from the warm conveyor belt (rearward sloping model) ascending a cold frontal zone (without line convection being present). (b) The vertical velocity of a parcel of air ascending the front. Note that the ascent is (approximately) uniform away from the surface frontal position. Also shown is the resultant rainfall rate (R) associated with uniform ascent. (c) Embedded instabilities superimposed on the frontal surface. For clarity, the frontal-scale ascent has been omitted. (d) The vertical velocity and rainfall rate, after modification by Conditional Symmetric Instability.

convection is so much greater than that in the rolls, it has not been shown on the diagram but the result is to enhance the banded nature of the rainfall.

The presence of instabilities embedded within the frontal surface leads to non-uniformities in the frontal precipitation, the scale of these being typically 50 km in the cross-frontal direction and some 100–200 km in the along-frontal direction.

The rolls are embedded within the ascending air of the conveyor belt as it rises up the frontal surface. Hence the resulting lines of heavier rain will gradually move away from the surface front. Given the right conditions, these will be replaced by further rolls developing in the source region.

References

Bennetts, D.A. and Hocking, L.M. 1973 On nonlinear Ekman and Stewartson layers in a rotating fluid. *Proc R Soc London*, A, **333**, 469–489.

Bennetts, D.A. and Hoskins, B.J. 1979 Conditional symmetric instability — A possible explanation for frontal rainbands. *Q J R Meteorol Soc*, **105**, 945–962.

Bennetts, D.A., Grant, J.R. and McCallum, E. (1989) An introductory review of fronts. Part II: A case-study. (To appear in *Meteorol Mag*.)

Browning, K.A. and Pardoe, C.W. 1973 Structure of low-level jet streams ahead of mid-latitude cold fronts. *Q J R Meteorol Soc*, **99**, 619–638.

Emanuel, K.A. 1982 Inertial instability and mesoscale convective systems. Part II: Symmetric CISK in a baroclinic flow. *J Atmos Sci*, **39**, 1080–1097.

Hoskins, B.J. 1978 Baroclinic instability and frontogenesis. *In* Roberts, P.H. and Soward, A.M. (eds); Rotating fluids in geophysics. London, New York, San Francisco, Academic Press.

Hoskins, B.J. and Bretherton, F.P. 1972 Atmospheric frontogenesis models: Mathematical formulation and solution. *J Atmos Sci*, **29**, 11–37.

Matejka, T.J., Houze, R.A., jun., and Hobbs, P.V. 1980 Microphysics and dynamics of clouds associated with mesoscale rainbands in extratropical cyclones. *Q J R Meteorol Soc*, **106**, 29–56.

Met.O.982

THE METEOROLOGICAL MAGAZINE

1988 *Volume 117*

The responsibility for facts and opinions expressed in the signed articles and letters published in this magazine rests with their respective authors.

Published for the Meteorological Office by Her Majesty's Stationery Office

INDEX

551.553.21(540)

A note on the normal dates of onset of summer monsoon over south peninsular India

I. Subbaramayya, S. Vivekananda Babu* and C.V. Naidu

Department of Meteorology and Oceanography, Andhra University, Waltair, India

Summary

There are some large differences between the dates of onset of the summer monsoon published by the India Meteorological Department (1943) and those obtained by Subbaramayya *et al.* (1984). Consequently the normal dates of onset of the summer monsoon over south peninsular India have been re-examined by the method of change in slope of cumulative rainfall. The dates obtained by the slope method at the west coast stations in this investigation have been found to agree with those obtained by Subbaramayya *et al.* It is not possible to determine the onset dates at stations east of the Western Ghats in the south exclusively by the slope method because of the heavy pre-monsoon thunderstorm rains. In view of the similarity of the basic causes of the pre-monsoon rains and the monsoon rains, it is suggested that the pre-monsoon thunderstorm rains over south peninsular India are referred to as 'local monsoon' or 'little monsoon'.

1. Introduction

The normal dates of onset of the summer monsoon over India and the surrounding region (Fig. 1(a)) were published by the India Meteorological Department (1943). Those dates were obtained from the characteristic rise in the cumulative 5-day mean rainfall curves at a number of stations. An alternative approach was taken by Subbaramayya *et al.* (1984) who prepared a chart (Fig. 1(b)) of mean dates of onset based on the principle that the onset of monsoon at any place should be associated with the first westward-moving rain-storm of the summer season in that area. In the southern parts of the country, however, an additional condition, namely that the rains should be accompanied by strong westerlies, was also considered. Though, in general, Figs 1(a) and 1(b) agree, there are some major differences over the south peninsula. For example, the mean date of onset over the extreme south peninsula according to Fig. 1(b) is 20 May while Fig. 1(a) shows it as 1 June. This is quite a large difference and, therefore, the normal dates of onset by the method of cumulative mean pentad rainfall curves have been re-examined. It was particularly important to do this because Ananthakrishnan *et al.* (1967) have referred to another chart published by the India Meteorological Department in 1943. The commonly known chart in Fig. 1(a) is a modified version of this earlier chart and bears significant differences from it. The modifications were made specially in the areas where the pre-monsoon thunderstorm rains merge into monsoon rains; this was done by experienced meteorologists considering other factors such as clouds, isobaric gradient and winds. The rules they followed in modifying the chart are, however, not known.

2. Data and analysis

The India Meteorological Department (1965) has published the normals of daily accumulated rainfall at all the synoptic stations for the period 1901 to 1950. Cumulative mean rainfall curves for a number of stations have been prepared starting from the beginning of March. To determine the date of onset at any station, two tangents to the cumulative rainfall curve were drawn, where the rates of increase of cumulative rainfall are constant, before and after an increase of slope, see Figs 2 and 3. The meeting point of the two tangents is taken as the date of onset at that station. At some places the increase in the trend of the cumulative rainfall curves occurred in two stages. In such cases two dates have been

* Now at Indian Institute of Technology, New Delhi.

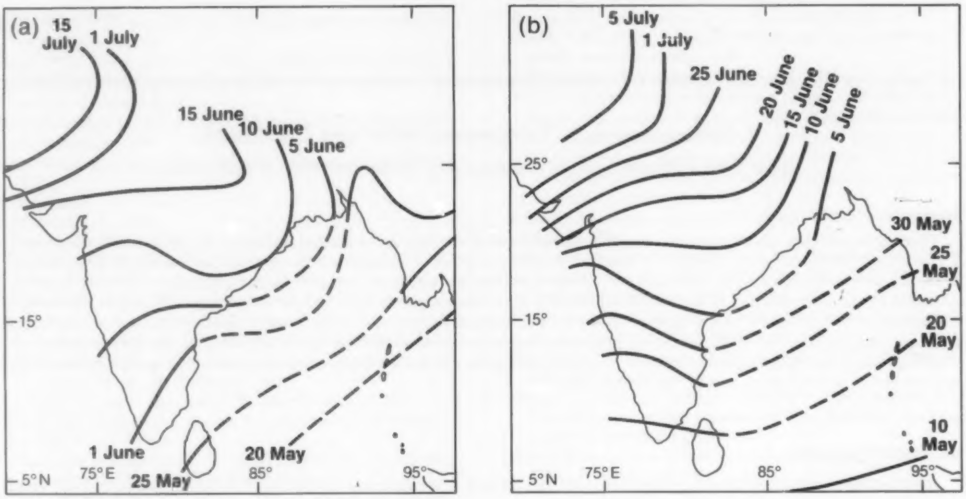


Figure 1. Normal dates of onset of the summer monsoon, (a) after India Meteorological Department (1943), and (b) after Subbaramayya *et al.* (1984).

obtained corresponding to the two stages of increase in the slope of the curves. The dates thus obtained are plotted on a chart and their variations are examined in the light of synoptic developments in the area.

3. Results and discussion

3.1 *Onset dates*

The cumulative mean rainfall curves at some of the stations are presented in Figs 2 and 3 (Fig. 4 shows the location of the stations and the abbreviations used to identify them). The west coast stations (e.g. Trivandrum (TRV), Cochin (CHN) Mangalore (MNG), and Bombay (BMB)), the Arabian sea island stations (e.g. Amini (AMN) and Minicoy (MNC)) and north peninsular India stations (e.g. Malegaon (MLG), Hyderabad (HYD) and Kalingapatnam (KLM)) show a sudden increase in the trend of the curve and the date of onset could be determined without difficulty as set by the criterion (see Fig. 2).

At stations in the extreme south (e.g. Palayankottai (PLK) and Pamban (PBN)), the slope of the curve is steeper in April itself and less steep in the monsoon months of June and July (see Fig. 3). At stations further north and east on the east coast (e.g. Cuddalore (CDL) and Nellore (NLR)) of south peninsula, the rainfall curves have a double bend with an inflexion in between. At Nellore, however, there is a second steady steep rise in the curve after the second bend. Consequently two dates have been obtained. Similarly at some interior stations (e.g. Bangalore (BNG) and Chitradurga (CHT)) the curves also have a double bend. But in these cases, the initial change in the slope itself is quite pronounced and persistent for a long time. At stations further north (e.g. Cuddapah (CDP), Bijapur (BJP) and Gulbarga (GLB)), the increase in slope occurred in two stages. Therefore, the dates at these stations were determined on the basis of the second stage increase in the slope of the curves.

The dates of onset of the monsoon as determined from the above type of diagrams are presented in Fig. 4. The dates over north peninsula are quite comparable to those in Fig. 1(a) as well as Fig. 1(b).

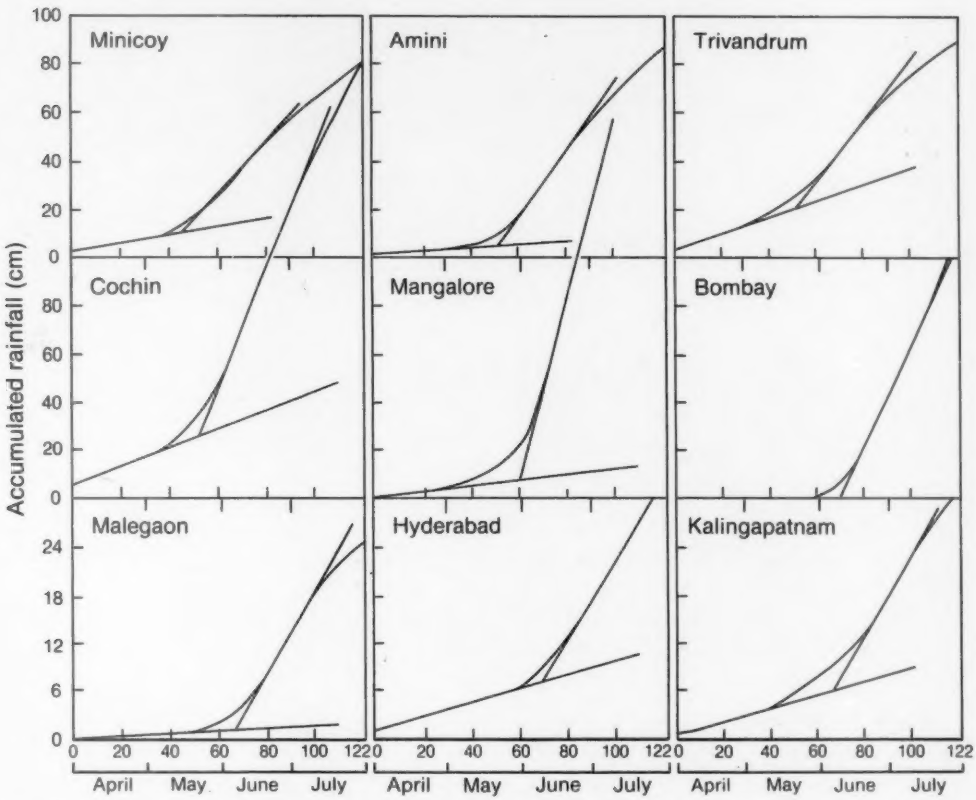


Figure 2. Cumulative mean rainfall curves at a selection of stations with days from the beginning of April shown. See section 2 for an explanation of the line construction.

However, in the extreme south on the west coast, the date of onset according to the present analysis is as early as 20 May — this agrees with Fig. 1(b) but not Fig. 1(a). To the east of the Western Ghats the dates are very different from those in Figs 1(a) and 1(b). There is in fact a discontinuity in the dates on either side of the Ghats. The dates on the eastern side are early; in the south the difference can be as much as 6 weeks. There is a narrow area in the Ghats where the dates are later by 7–10 days compared to those on the western side at corresponding latitudes.

The early rains over south peninsula can be referred to as pre-monsoon thunderstorm rains. These rains were overlooked in the studies by the India Meteorological Department which resulted in Fig. 1(a); continuous onset-date lines across the Ghats were drawn by considering other meteorological factors as mentioned in section 1. In that process, the onset dates on the west coast also might have been altered. Elsewhere the onset dates in the south, according to the slope-change method, also agree with those in Fig. 1(b) obtained by Subbaramayya *et al.* (1984).

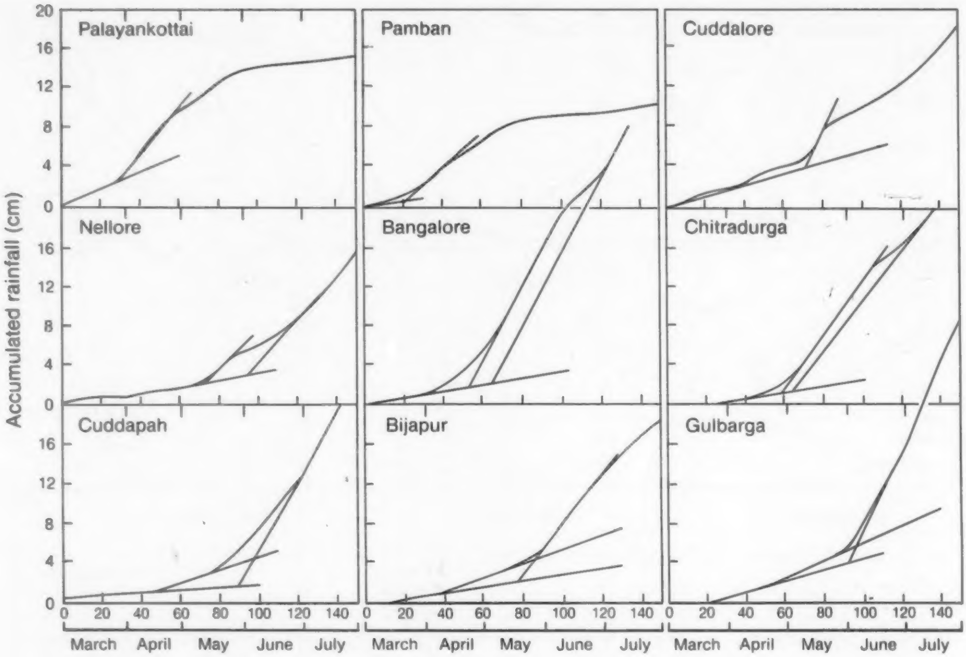


Figure 3. As Fig. 2, but for another selection of stations with days from the beginning of March shown.

3.2 *Pre-monsoon thunderstorm rains*

As summer progresses, a north–south elongated low develops over the western parts of peninsular India in March due to excess heating of the land (Fig. 5(a)) and high pressures with anticyclonic circulations appear over the Bay of Bengal and Arabian Sea. During April the heat low deepens and its centre is displaced north-eastwards (Fig. 5(b)). However, a trough extends from this low to the extreme south of peninsular India. A wind discontinuity exists in the heat low between northerlies over the west coast and south-easterlies/southerlies over the south-east peninsula. The latter veer to become south-westerlies over northern parts of the east coast (Figs 6(a) and 6(b)). The southerlies, as they come from south Bay of Bengal, have maritime tropical air-mass characteristics and when that air passes over the heated land convective precipitation occurs.

During this period, troughs in the easterlies in the south progress westward and when they come to the longitude of the heat low, the easterly trough is intensified and the south-easterlies over the east peninsula penetrate farther into the interior. Similarly when a westerly trough in the north is in phase with the heat low, the south-easterlies are again strengthened. On such occasions the convective activity is enhanced.

As the summer season further progresses through May and June, the heat low is not only deepened but is also displaced initially northwards and later to the north-west (Figs 5(c) and 5(d)); this ultimately culminates in the establishment of a continental-scale heat low with its centre over north-west India and Arabia. During this period the anticyclones over the Bay of Bengal and Arabian Sea weaken and a

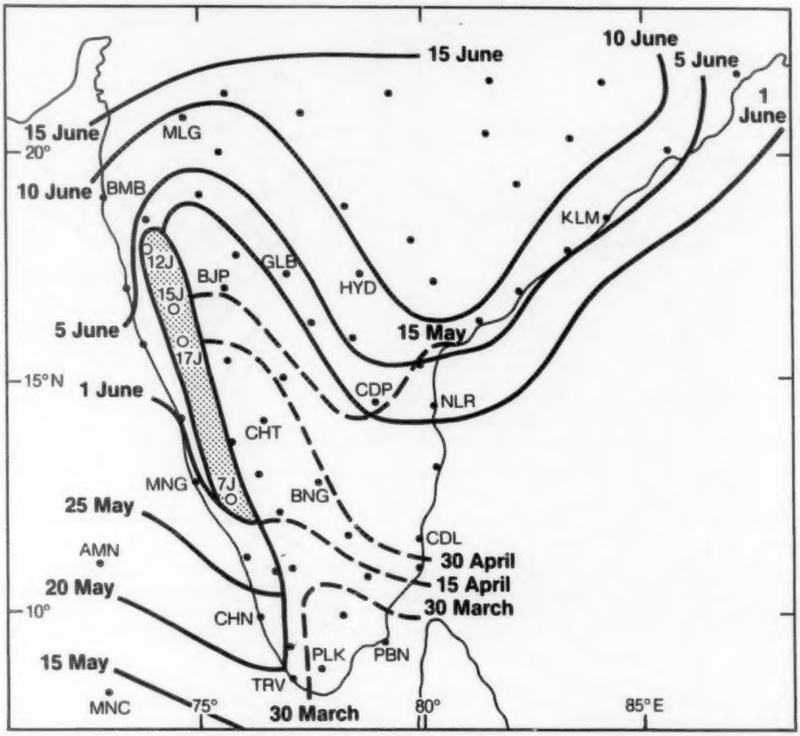


Figure 4. Normal dates of onset of the monsoon by the method described in section 2. The dots indicate the location of stations and those mentioned in the text are accompanied by an abbreviated name. The dashed lines indicate the dates of change of slope of cumulative rainfall curves which do not agree with the normal dates of onset. 12J etc. in the dotted area (Western Ghats) represent 12 June etc.

pressure gradient across the equator is established. As a result of this, the equatorial maritime air from the southern hemisphere is driven into the heat low over central and west Asia, which is responsible for the monsoon rainfall over India.

It is clear from the above sequence of events that the physical basis of the pre-monsoon rains is basically the same as that of the monsoon rains. However, while the monsoon rains are associated with the equatorial maritime air mass, the pre-monsoon rains are due to the tropical maritime air mass. The general circulation associated with monsoon rains is of continental scale while that associated with the pre-monsoon rains is of subcontinental scale. It is, therefore, appropriate to refer to the southerlies/ south-westerlies over the Indian peninsula during April and early May, and the associated rains, as 'local monsoon' or 'little monsoon'.

The cumulative rainfall curves in south-east and east central peninsula first showed increases in their slope because of the little monsoon. But with the advance of the equatorial maritime air from the Arabian Sea, the rains over the lee side of the Ghats have decreased due to rain-shadow effect. However, at stations in south central and east peninsula the rainfall has again increased due to monsoon depressions, depending on the extent of their influence to the south.

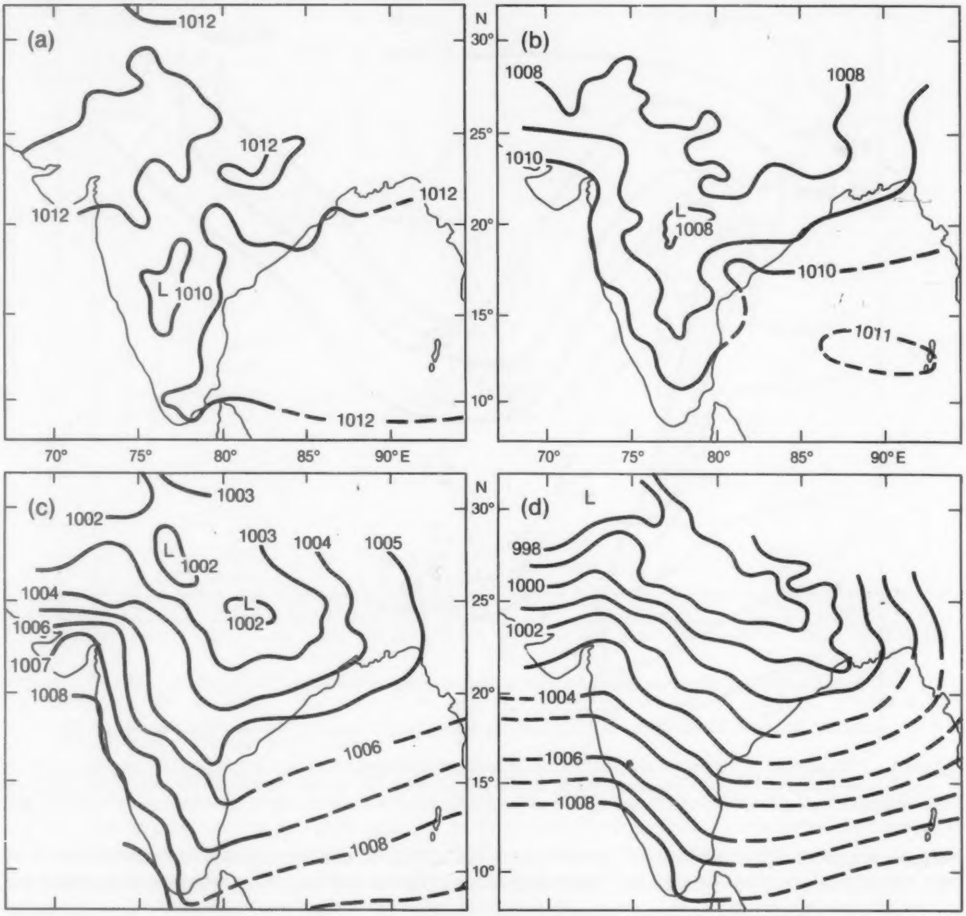


Figure 5. Mean-sea-level pressure distributions (mb) in the fourth pentad of (a) March, (b) April, (c) May, and (d) June.

It is not clear why the cumulative rainfall curves at some stations on the Ghats showed change of slope at dates much later (7–10 days) than at the west coast stations. This needs a more detailed study of the synoptic climatology of the rains at those stations.

4. Conclusions

The normal dates of onset of the monsoon at the stations on the west coast of south peninsular India, as determined by the method of change in slope of cumulative rainfall curves, are much earlier than those published by the India Meteorological Department (1943). The dates agree with those obtained by Subbaramayya *et al.* (1984) based on the principle that the onset of monsoon should be associated with the first westward-moving rain-storm of the summer season.

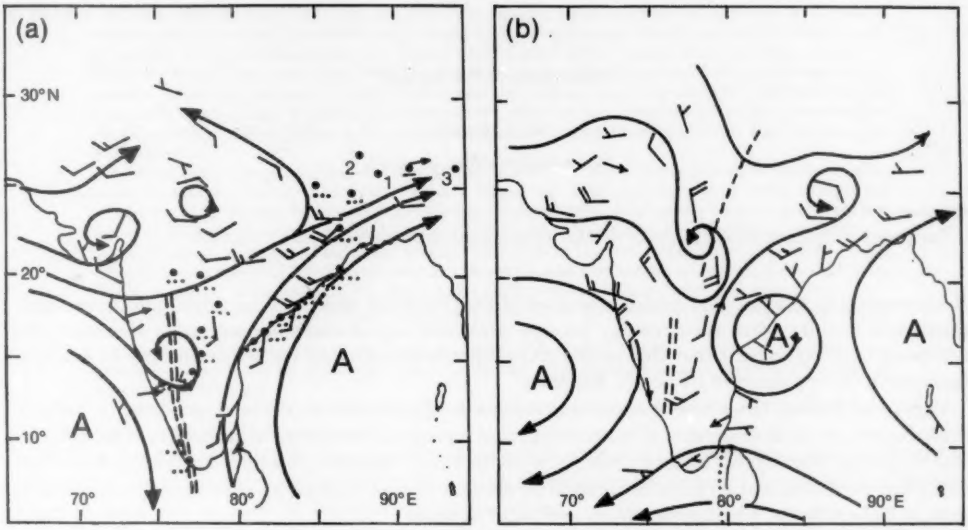


Figure 6. Streamlines at (a) 0.6 km and (b) 850 mb at 00 GMT on 20 April 1988. In (a) rainfall is shown: three dots in a line indicate rainfall less than or equal to 0.25 cm and the short full lines indicate rainfall between 0.25 and 0.5 cm, and larger rainfall amounts are given to the nearest centimetre. The double dashed line indicates wind discontinuity, and in (b) the single dashed line indicates a westerly trough and the dotted line a trough in the easterlies.

The monsoon rains in the extreme south, east of the Western Ghats, are less intense than the so-called pre-monsoon rains. The pre-monsoon rains, as they are also associated with differential heating and reversed local circulations, may be referred to as the 'local monsoon' or 'little monsoon'.

References

Ananthakrishnan, R., Acharya, U.R. and Ramakrishnan, A.R. 1967 Forecasting Manual Part II, 18: Monsoons of India, p.1. New Delhi, India Meteorological Department.

India Meteorological Department 1943 Climatological atlas for Airmen, p.3. New Delhi, India Meteorological Department.

1965 Normals of daily accumulated rainfall. New Delhi, Government of India.

Subbaramayya, I., Babu, S.V. and Rao, S.S. 1984 Onset of the summer monsoon over India and its variability. *Meteorol Mag*, **113**, 127–135.

551.501.1:551.501.3:551.5(09)

The first 'obs' book?

M.E. Crewe
Meteorological Office, Bracknell

Summary

The scheme proposed by Robert Hooke in 1663 for observing and recording the weather is discussed.

It is tempting to imagine that methodical ways of observing the weather were introduced in the mid-nineteenth century when meteorology became organized on an international basis. However, the following extracts suggest that the natural philosophers who formed the Royal Society of London anticipated the requirement by nearly 200 years.

Papers by Robert Hooke, who was the first curator of experiments at the Royal Society, include contributions to the development of meteorology that represent a watershed in the history of the subject. One such is his 'Method for making a history of the weather'. However, it is not clear whether the work published by Hooke was all his own creation or whether he was inspired by contemporary luminaries such as Robert Boyle, Christopher Wren and Isaac Newton.

According to Birch (1757) 'Mr Hooke's paper concerning the observables for making a history of the weather was read...' at the meeting of 7 October 1663. A printed version was published by Sprat in 1667 with a French translation published in Geneva in 1669. The following extracts are transcribed from the second edition of Sprat's *The history of the Royal Society of London* (Sprat 1702), a copy of which is held in the National Meteorological Library, Bracknell.

Hooke starts:

> For the better making a history of the weather, I conceive it requisite to observe,
>
> 1. The Strength and Quarter of the Winds, and to register the Changes as often as they happen: both which may be very conveniently shewn, by a small addition to an ordinary Weather-clock.
>
> 2. The Degrees of Heat and Cold in the Air; which will be best observed by a sealed *Thermometer*, graduated according to the Degrees of *Expansion*, which bear a known proportion to the whole bulk of Liquor, the beginning of which gradation, should be that dimension which the Liquor hath, when encompassed with Water, just beginning to freeze, and the degrees of *Expansion*, either greater or less, should be set or marked above it or below it.
>
> 3. The Degrees of Dryness and Moisture in the Air; which may be most conveniently observed by *Hygroscope*, made with the single beard of a wild Oat perfectly ripe, set upright and headed with an *Index*, after the way described by *Emanuel Magnan*; the conversions and degrees of which, may be measured by divisions made on the rim of a Circle, in the *Center* of which, the *Index* is turned round: The beginning or Standard of which Degree of *Rotation*, should be that, to which the *Index* points, when the beard, being throughly wet, or covered, with Water, is quite unwreathed, and becomes straight. But because of the smalness of this part of the Oat, the cod of the wild *Vetch* may be used instead of it, which will be a much larger *Index*, and will be altogether as sensible of the changes of the Air.

At this time there was much interest in the development of thermometers and hygroscopes. In 1663/64 Hooke devised a device to standardize the calibration of thermometers; this shows that he appreciated the need for standardization and was able to implement his ideas. Also, at about the same time, Dr Goddard of the Society was investigating a hygroscope which used a lute string (gut?) with pulleys and a cylinder.

Hooke continues:

> 4. The degrees of Pressure in the Air: which may be several wayes observed, but best of all with an Instrument with Quicksilver, contrived so, as either by means of water or an *Index*, it may sensibly exhibit the minute variations of the Action.

5. The constitution and face of the Sky or Heavens; and this is best done by eye; here should be observed, whether the Sky be clear or clouded; and if clouded, after what manner; whether with high Exhalations or great white Clouds, or dark thick ones. Whether those Clouds afford Fogs or Mists, or Sleet, or Rain, or Snow, etc. Whether the under side of those Clouds be flat or waved and irregular, as I have often seen before thunder. Which way they drive, whether all in one way, or some one way, some another; and whether any of these be the same with the Wind that blows below; the Colour and face of the Sky at the rising and setting of the Sun and Moon; what Haloes or Rings may happen to encompass those Luminaries, their bigness form and number.

6. What Effects are produc'd upon other bodies: As what Aches and Distempers in the bodies of men: what Diseases are most rife, as Colds, Fevours, Agues, etc. What putrefactions or other changes are produc'd in other Bodies; As the sweating of Marble, the burning blew of a Candle, the blasting of Trees and Corn; the unusual sprouting, growth, or decay of any Plants or Vegetables: the putrefaction of bodies not usual; the plenty or scarcity of Insects; of several Fruits, Grains, Flowers, Roots, Cattel, Fishes, Birds, any thing notable of that kind. What conveniences or inconveniences may happen in the year, in any kind, as by floods, droughts, violent showers, etc. What nights produce dews and hoar-frosts, and what not?

7. What Thunders and Lightnings happen, and what Effects they produce; as souring of Beer or Ale, turning Milk, killing Silk-worms, etc.

8. Any thing extraordinary in the Tides; as double Tides later or earlier, greater or less Tides than ordinary, Rising or drying of Springs; Comets or unusual Apparitions, new Stars, *Ignes fatui** or shining Exhalations, or the like.

They should all or most of them be diligently observed and registered by some one, that is alwayes conversant in or neer the same place.

Having listed what should be observed, Mr Hooke then considers how these observations should be recorded 'so as to be most convenient for the making of comparisons, requisite for the raising *Axioms*, whereby the Cause or Laws of Weather may be found out.'

Hooke then prescribes the forerunner to the daily registers of meteorological observation which are now used. The related illustration from Sprat's book is reproduced. The recording of wind, temperature, moisture and pressure seems to have been relatively straightforward, but how to record the 'faces of the Sky' he clearly found more perplexing:

But for the faces of the Sky, they are so many, that many of them want proper names; and therefore it will be convenient to agree upon some determinate ones, by which the most usual may be in brief exprest. As let *Cleer* signifie a very cleer Sky without any Clouds or Exhalations: *Checker'd* a cleer Sky, with many great white round Clouds, such as are very usual in Summer. *Hazy*, a Sky that looks whitish, by reason of the thickness of the higher parts of the Air, by some Exhalation not formed into Clouds. *Thick*, a Sky more whitened by a greater company of Vapours: these do usually make the *Luminaires* look bearded or hairy, and are oftentimes the cause of the appearance of Rings and Haloes about the *Sun* as well as the *Moon*. *Overcast*, when the Vapours so whiten and thicken the Air, that the *Sun* cannot break through; and of this there are very many degrees, which may be exprest by a *little, much, more, very much overcast*, etc. Let *Hairy* signifie a Sky that hath many small, thin and high Exhalations, which resemble locks of hair, or flakes of Hemp or Flax: whole varieties may be exprest by *straight* or *curv'd* etc. according to the resemblance they bear. Let *Water'd* signifie a Sky that has many high thin and small Clouds, looking almost like water'd Tabby, called in some places a Mackeril Sky. Let a Sky be called *Waved*, when those clouds appear much bigger and lower, but much after the same manner. *Cloudy*, when the Sky has many thick dark Clouds, *Lowring*, when the Sky is not very much overcast, but hath also underneath many thick dark Clouds which threaten rain. The signification of *gloomy, foggy, misty, sleeting, driving, rainy, snowy*, reaches or racks *variable*, etc. are well known, they being very commonly used.

Experienced observers may judge for themselves how near Hooke was to the ten main types of cloud —and 130 years before Luke Howard.

Mr Hooke concludes by advocating a global, or at least national, network of observers working to a common standard. Then 'the Method of using and digesting those so collected Observations...will be more advantageously considered' because 'A workman being then best able to fit and prepare his Tools, for his work, when he sees what materials he has to work upon.'

Having read these instructions it seems a shame that they were never implemented as they appear adequate for setting up a basic observing network. Why then were Hooke's proposals not implemented?

* Will-o'-the wisp

A SCHEME

At one View repreſenting to the Eye the Obſervations of the Weather for a Month.

Dayes of the Month and place of the Sun.	Remarkable houre.	Age and ſign of the Moon at Noon.	The Quarters of the Wind and its ſtrength.	The Degrees of Heat and Cold.	The Degrees of Drineſs and Moyſture.	The Degrees of Preſſure.	The Faces or viſible ap peafances of the Sky.	The Notableſt Effects.	General Deductions to be made after the ſide is fitted with Obſervations: As,
14 ♊ 12.46	4 8 12 4 8 12	27 ♉ 9. 46. Perigeu.	W. 2. 3. 2 3 W.S W.1	9 $\frac{1}{4}$ 12 16 10 7	2 5 2 8 2 5	29 $\frac{1}{10}$ 29 $\frac{1}{8}$ 29 $\frac{1}{8}$	Clear blew. but yellowiſh in the N. E. Clowded toward the S. Checker'd blew.	A great dew. Thunder, far to the South. A very great Tide.	From the laſt Q. of the *Moon* to the Change the Weather was very temperate, but cold for the ſeaſon; the Wind pretty conſtant between N. & W. A little before the laſt great Wind and till the Wind roſe at its higheſt, the Quick-ſilver continu'd deſcending til it came very low: after wch it began to re aſcend, &c.
15 ♊ 13.40	8 4 6 10	28 ♉ 24.51	N. W. 3 4 N. 2 1	9 8 $\frac{1}{2}$ 7	28 $\frac{1}{3}$ 2 9 2 10	29 $\frac{1}{16}$ 29	A clear Sky all day, but a little Checker'd at 4. P. M. at Sunſet red and hazy.	Not by much ſo big a Tide as yeſterday. Thunder in the North.	
16 ♊ 14.37	10	N. Moon. at 7. 25' A. M. ♊ 10. 8.	S. 1	10	1 10	28 $\frac{1}{2}$	Overcaſt and very lowring.	No dew upon the ground, but very much upon Marble-ſtones, &c.	
		&c.	&c.	&c.	&c.	&c.	&c.		

Z 2 D I-

One reason was that the economic and political climate was not ready, and another may be that the seventeenth century natural philosophers were too busy discovering and inventing, and had little time for routine, applied science. The range of interests was remarkable; for example, Waller reported that Hooke was involved with such divers matters as astronomy, optics, geometry, horology, the trade of felt making, music and sound, the structure of animals' muscles, flying, hydrology, earthquakes, navigation, etc. Also after the great fire of London in 1666, the Royal Society, the Lord Mayor and the King were so impressed with Hooke's model for rebuilding the City that he was appointed City Surveyor.

In his book *Micrographia*, published at the beginning of 1665, Hooke described, among other things, 'the Baroscope, Hygroscope, an Instrument to graduate Thermometers'. So it is remarkable that this 'Method of making a history of the weather' lacks any reference to a rain-gauge. It seems likely, however, that Hooke did not wish to poach ideas from Wren who was not only a friend but had proposed a

'Weather-clock' some time before 1664. By 1669, according to Waller (1705), 'Some Contrivances were shewn by him to be added to the Weather-clock, as a Hygroscope, a contrivance to measure the quantity of Rain, Snow or Hail fallen in a certain time; which Engine was soon perfected in all its parts, and set up in the Repository.' In fact Hooke built and refined Wren's Weather-clock which was perhaps the first automatic weather station, complete with tipping-bucket rain-gauge — but that is another story!

Acknowledgement

I am grateful to the Librarian of the Royal Society for providing some additional references.

References

Birch, T. 1757 The history of the Royal Society of London for the improving of natural knowledge. Vol. I. London, printed for A. Millar in the Strand.

Sprat, T. 1702 The history of the Royal Society of London, for the improving of natural knowledge. Second edition corrected. London, printed for Rob. Scot, Ri. Chiswell, Tho. Chapman and Geo. Sawbridge.

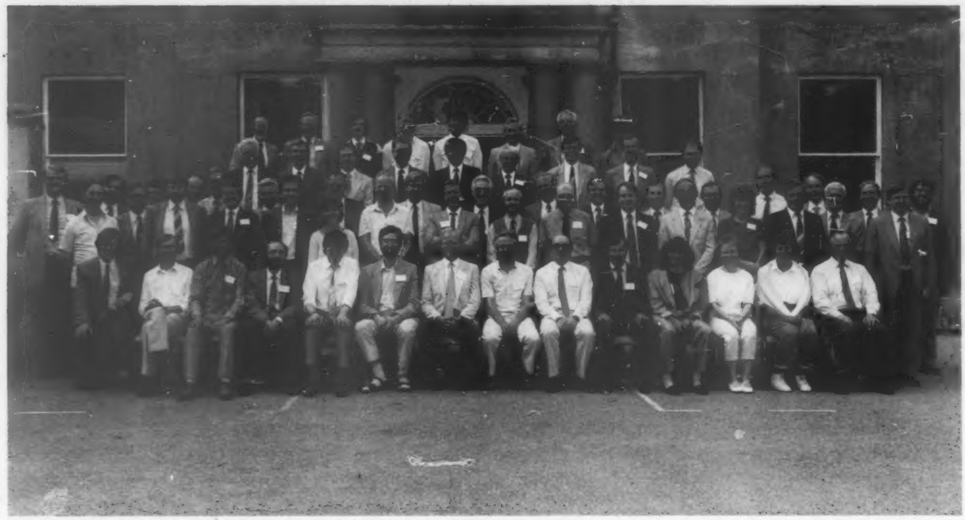
Waller, R. 1705 The posthumous works of Robert Hooke... Containing his Cutlerian Lecture and other discourses. London, printed by Sam. Smith and Benj. Walford at the Princes Arms in St Paul's Church-yard.

Conference report

Summer School on the October Storm, Meteorological Office College, Shinfield Park, 20—22 July 1988

This was the third summer school organized by the Meteorological Office College, following very successful ones on the diagnosis of numerical weather prediction (NWP) products in 1987 and mesoscale meteorology in 1985. The original idea was to hold them every two years but the events of 15/16 October 1987 and the intense interest raised by the storm and its prediction led to a summer school being held a year early. It was a highly popular event with 69 people taking part and further applicants being turned away. Unlike previous summer schools the majority of participants had a background of forecasting. There was a large Meteorological Office contingent from outstations, Headquarters research branches and the Central Forecasting Office; three universities were represented and there were participants from Jersey, Ireland, France, Germany and The Netherlands.

The great strength of this type of meeting is the wide range of backgrounds of those attending and the opportunities it offers to widen one's own experience, both during the case-study sessions and in conversation afterwards in the bar. It was shorter than the previous summer schools, lasting three days, which allowed only just enough time to become familiar with the subject. The participants were divided into nine groups of about six people, with an adviser assigned to each group to guide them through the large volume of case-study material. This included satellite pictures, print-outs from the FRONTIERS radar network, charts of plotted observations and a wide range of model products. The order of events was: case-study work, followed by group presentations and finally lectures from the experts. On the whole the idea that the groups sorted out their own ideas before listening to the lectures worked well, and indeed there was lively discussion throughout all the case-study sessions.



The first of the two case-studies concerned the analysis of the meteorological situation. All the observational evidence during the 24 hours leading up to the storm was presented as well as analyses and forecasts from the model run which, with adjustments and fine tuning after the event, was found to give the best forecast. This case-study provided an excellent example of the problems of analysis in the data-sparse regions over the oceans. Accurate analysis in these regions is highly dependent on the observations received from ships which unfortunately often prove to be unreliable. In a study of all the re-analysed surface charts in the period leading up to the storm it was found that of the 60 ship reports which lay within the area of interest, 17 were suspect in either their pressure or wind report. Central to the analysis of the system, which deepened to become the destructive low centre, was the associated cloud structure identifiable on satellite imagery as a 'cloud head' or wedge-shaped cloud mass lying in the cold air and separated from the main frontal cloud by an incursion of dry stratospheric air. We heard a great deal about this type of cloud structure in the lectures which followed. Geoff Monk (Meteorological Office), in a fascinating presentation of cloud imagery from other notable storms in the North Atlantic, gave evidence that most if not all cases of this characteristic cloud formation are followed by explosive cyclogenesis. In this case the cloud head developed some 36 hours before the storm reached its full strength. His explanation of the physical processes at work was followed up in more detail in a lecture by Glenn Shutts (Meteorological Office) which required an ability to think clearly in three dimensions.

In the interlude between the two case-studies we heard from Brian Hoskins (University of Reading) on some theoretical aspects of cyclogenesis and, in an additional lecture fitted in on Wednesday evening, Jean-François Geleyn of the French Meteorological Service gave us the French perspective on the storm. Like their UK counterparts they were faced with the problem of how to interpret conflicting numerical guidance, in this case from their own models and ECMWF. In the event they issued warnings of winds gusting to 150 km per hour over northern France 48 hours before the storm, though the forecast was downgraded later principally as a result of being influenced by a very misleading T+36-hour forecast from ECMWF.

The second case-study concerned the forecast material available from various runs of the fine-mesh and mesoscale models. Central to the case-study was the operational fine-mesh forecast from 00 GMT on 15 October which gave such poor guidance at the time. Its failure to develop an intense low led to a great deal of discussion on the accuracy of the initial analysis, and participants at the summer school could make use of a wide range of model output not normally available to the forecaster. The merits of various methods of interpreting NWP products were given a good airing. Martin Morris (Meteorological Office), in a lecture towards the end of the meeting, advocated the use of forecast vertical velocity and thermal advection to identify development areas. Charts of potential vorticity and Q-vectors featured much during the three days and there was strong recommendation from the theoreticians for their usefulness as a diagnostic tool. Whatever the merits of a diagnostic product as a means of understanding the meteorological developments after the event, its usefulness to forecasters depends on what it can tell them about the likely accuracy of the current numerical prediction they are faced with. Although there are grounds for believing that potential vorticity may be useful in this respect, this was not demonstrated at the summer school. There is indeed much yet to learn about the interpretation of numerical forecasts.

The remaining material available for the second case-study included the forecasts from the operational fine-mesh and mesoscale models with data time 12 GMT on the 15th. There were also forecasts from an experimental version of the fine-mesh model with a new data-assimilation scheme. In all cases the forecasts were a distinct improvement on those from the 00 GMT run and gave some indication of strong winds over south-east England. The mesoscale model was particularly impressive in this respect, though it was not the version in use at the time. Less impressive was the layout of the mesoscale model output which had incomprehensible headings and so many contours and symbols on some charts that they became illegible.

Reading through the questionnaires filled in by the participants it is clear that the summer school was considered a great success. Its smooth running was due to much hard work by Roy Kershaw and Will Hand at the College and by members of the Forecasting Research Branch of the Meteorological Office who provided the case-study material. Certainly a meeting with this format successfully brings together the different disciplines within meteorology and is well worth continuing in the future.

C.D. Hall

Satellite photograph — 10 October 1988 at 0926 GMT

This visible image shows two separate cloud systems as they approach western Europe. The northern system, seen as a 'comma' shaped cloud band, originated some 24 hours earlier as a band of enhanced convection within an unstable polar air mass. The band marks a cold frontal zone. There is little evidence from either the imagery or surface observations of a corresponding warm front.

The southern cloud area, centred off north-west Iberia was associated with the major upper-tropospheric jet stream. Cirrus ahead of the system is seen over Biscay, whilst further west the cloud progressively thickens and is partly convective. Within the low cloud at the rear of the system, a small vortex can be seen marking the surface low-pressure area.

During the following 24–36 hours, the cloud systems gradually merged to form an instant occlusion. As the cloud from the northern system reached the British Isles considerable rainfall occurred, with parts of south-west Ireland receiving more than 50 mm. Serious flooding occurred in Cornwall where over 40 mm was recorded.

Photograph by courtesy of University of Dundee

Meteorological Magazine

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe the results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles for publication and all other communications for the Editor should be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ and marked 'For *Meteorological Magazine*'.

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately.

Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary*.

References should be made using the Harvard system (author, date) and full details should be given at the end of the text. If a document referred to is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to.

Tables should be numbered using roman numerals and provided with headings. We consider vertical and horizontal rules to be unnecessary in a well-designed table; spaces should be used instead.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and difficult to read. Keep notation as simple as possible; this makes typesetting quicker and therefore cheaper, and reduces the possibility of error. Further guidance is given in BS1991: Part 1: 1976 and *Quantities, Units and Symbols* published by the Royal Society.

Illustrations

Diagrams must be supplied either drawn to professional standards or drawn clearly, preferably in ink. They should be about 1½ to 3 times the final printed size and should not contain any unnecessary or irrelevant details. Any symbols and lettering must be large enough to remain legible after reduction. Explanatory text should not appear on the diagram itself but in the caption. Captions should be typed on a separate sheet of paper and should, as far as possible, explain the meanings of the diagrams without the reader having to refer to the text.

Sharp monochrome photographs on glossy paper are preferred: colour prints are acceptable but the use of colour within the magazine is at the Editor's discretion. In either case contrast should be sufficient to ensure satisfactory reproduction.

Units

SI units, or units approved by WMO, should be used.

Copyright

Authors wishing to retain copyright for themselves or for their sponsors should inform the Editor when they submit contributions which will otherwise become UK Crown copyright by right of first publication.

It is the responsibility of authors to obtain clearance for any copyright material they wish to use before submitting it for publication.

Free copies

Three free copies of the magazine are provided for authors of articles published in it. Separate offprints for each article are not provided.

Meteorological Magazine **December 1988**

Editor: B.R. May
Editorial Board: R.J. Allam, W.H. Moores, P.R.S. Salter, P.G. Wickham

Vol. 117
No. 1397

CONTENTS

Contributions: It is requested that all communications to the Editor and books for review be addressed to the Director-General, Meteorological Office, London Road, Bracknell, Berkshire RG12 2SZ, and marked 'For *Meteorological Magazine*'. Contributors are asked to comply with the guidelines given in the *Guide to authors* which appears on the inside back cover. The responsibility for facts and opinions expressed in the signed articles and letters published in *Meteorological Magazine* rests with their respective authors. Authors wishing to retain copyright for themselves or for their sponsors should inform the Editor when submitting contributions which will otherwise become UK Crown copyright by right of first publication.

Subscriptions: Annual subscription £27.00 including postage; individual copies £2.30 including postage. Applications for postal subscriptions should be made to HMSO, PO Box 276, London SW8 5DT; subscription enquiries 01–211 8667.

Back numbers: Full-size reprints of Vols 1–75 (1866–1940) are available from Johnson Reprint Co. Ltd, 24–28 Oval Road, London NW1 7DX. Complete volumes of *Meteorological Magazine* commencing with volume 54 are available on microfilm from University Microfilms International, 18 Bedford Row, London WC1R 4EJ. Information on microfiche issues is available from Kraus Microfiche, Rte 100, Milwood, NY 10546, USA.

ISBN 0 11 728091 7 ISSN 0026–1149
